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Effects of experimental acidification and liming on soil organisms and decomposition in a Scots pine forest

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With 2 figures

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1. Introduction

The effects of deposition of acidic air pollutants on different ecosystems is today a topic under debate. Several investigations are being performed in order to evaluate different aspects within this relatively new problem area. In forest ecosystems, the research efforts have focussed first of all on possible effects on vegetation and on soil chemistry while other effects, for example on soil biota have been given little attention. In a review Abrahamsen & Dollard (1978) pointed at several possible interactions through vegetation and soil. They also concluded that today we do not know the longterm implications on, for instance, the nitrogen cycle within ecosystems or of increased leaching of metal cations.

Effects of experimental acidification on abundance of soil fauna have been reported (e. g. Lundkvist 1977; Hågvar 1978) as well as changes in root-parasite interactions (Shriner 1978). These studies indicate that soil organisms could be sensitive to increased acidity of the rain with subsequent effects, as pointed out by Tamm (1976), on mineralization and nutrient transformations.

To examine the extent to which soil biotic properties, such as amounts and activity of soil organism populations and rates of decomposition, were affected by increased acidification, a study was performed in an established field experiment with added sulphuric acid. The experiment included a treatment with lime. Liming has been suggested to be one way to overcome the acidification (e. g. Tamm 1976). A preliminary note on part of the results was given by Bååth et al. (1980).

2. Study area

The investigation was performed in an established optimum nutrition experiment at Norrliden, in the northern part of Sweden. The following site description is based on Holmen et al. (1976).

Table 1. Doses and application year of ground limestone and sulphuric acid in different treatments at the experimental area at Norrliden (HOLMEN et al. 1976)

Year	Control	Lime (Ca, kg ha^{-1})	Acid 1 (H_2SO_4, kg ha^{-1})	Acid 3 (H_2SO_4, kg ha^{-1})
1971	—	1960	50	50 + 50 + 50
1972	—	—	50	50 + 50 + 50
1973	—	—	50	50 + 50 + 50
1974	—	—	50	150
1975	—	—	50	150
1976	—	—	50	150
1977	—	—	—	—
1978	—	—	—	—

Table 2. Number of soil samples per block for different soil and soil organism characterization, and number of litter bags for decomposition measurements

	Control	Lime	Acid 1	Acid 3
Fungal mycelium	5$^{1)}$	5$^{1)}$	5$^{1)}$	5$^{1)}$
Bacteria:				
Numbers and biomass	5$^{1)}$	5$^{1)}$	—	5$^{1)}$
Physiological groups	5$^{1)}$	—	—	5$^{1)}$
Microarthropods	5	—	5	5
Enchytraeids	7	7	7	7
No. of litter bags:				
Needle litter	7+7	7+7	7+7	7+7
Root litter	7	—	—	7
Thickness of horizons	5	5	5	5
*p*H	7$^{1)}$	7$^{1)}$	7$^{1)}$	7$^{1)}$
Loss on ignition	5$^{1)}$	5$^{1)}$	5$^{1)}$	5$^{1)}$

Note. — Three blocks per treatment.

1) Bulked to form composite samples.

Table 3. Thickness, *p*H (H_2O) and loss on ignition of different soil layers at Norrliden. A standard error (s. e.) common to all treatments was calculated from the analysis of variance

		A Control	B Lime	C Acid 1	D Acid 3	s. e.
Thickness (cm)	A_{00}	2.0^{BD}	1.1^{A}	1.3	1.2^{A}	0.2
	$A_{01}-A_{02}$	3.3	2.5	3.1	2.8	0.4
	A_1-A_2	6.1^{CD}	6.7^{D}	8.7^{A}	9.1^{AB}	0.6
pH_{H_2O}	$A_{01}-A_{02}$	4.6^{B}	6.4^{ACD}	4.2^{B}	4.1^{B}	0.2
	A_1-A_2	4.6^{BD}	5.4^{ACD}	4.5^{B}	4.2^{AB}	0.1
	B	5.3^{D}	5.3^{D}	4.9	4.7^{AB}	0.1
Loss on ignition (% of dw)	$A_{01}-A_{02}$	*63.3*	*47.1*^{C}	*65.6*^{B}	*57.5*	*5.1*
	A_1-A_2	*5.1*^{D}	*3.7*	*3.4*	*2.8*^{A}	*0.7*
	B	*3.9*	*4.4*	*5.1*	*4.5*	*0.5*

Note. — Significant differences ($p < 0.05$) between treatments are indicated with the blockletters labelling the table columns.

The experimental area (64° 21′ N, 19° 46′ E) is situated about 260 meters above sea level. In 1953, after a clearcut in 1951 of the former Norway spruce-dominated [*Picea abies* (L.) KARST.] stand, it was planted with Scots pine (*Pinus sylvestris* L.). The soil material is till with a distinctly developed iron podzol. The mean annual temperature is 1.2 °C and the mean annual precipitation is about 600 mm. Fertilizer and acidification experiments with randomized blocks design were laid out in the area in 1970—71. In the present study only unfertilized plots where the soil acidity has been changed through additions of dilute sulphuric acid or lime (Table 1) were used.

3. Materials and methods

3.1. Sampling

On 5 October 1976, soil samples were collected in order to estimate the amounts and activity of soil organism populations in the different treatments (Table 2). At the same time the thickness of the different soil horizons was estimated and soil samples were collected for determination of *p*H and loss on ignition. *p*H was determined in a soil water mixture (1: 5 w/w for humus, 1: 3 w/w for mineral soils). Loss on ignition was determined at 550 °C. The results of these soil profile characterizations are presented in Table 3.

3.2. Litter decomposition

Brown 4-year-old needles were sampled in autumn 1976 at abscission from about 15-year-old Scots pines at Ivantjärnsheden (main site of the Swedish Coniferous Forest Project) Jädraås, Central Sweden and live roots were dug up from the $A_{01}-A_{02}$-layer of a nearby 120-year-old Scots pine stand. All storage of litter took place at −20 °C. The litter was dried at room temperature to a low moisture level (about 5−7% of dw). The dry weights were measured from separate subsamples dried at 85 °C until constant weight. The variation in moisture level was less than ± 0.5% of litter dw ($n = 10$). Needle litter (sample size 1−2 g) was enclosed in terylene net litter-bags with a mesh size of 1 mm and measuring 8 × 8 cm.

Pieces of root litter with a diameter of 2−3 cm freed from sand particles and loose bark were cut into 10 cm pieces. One such piece was enclosed in each litter-bag measuring 3 × 12 cm.

The litter-bags were incubated on 5 October 1976 on the A_{00}-layer (needle litter) and in the A_{01}—A_{02}-layer (root litter). For needle litter 14 litter-bags in each plot were used. Root litter-bags were incubated in the Control and Acid 3 treatments only, in each plot.

After collection of the litter-bags after about one and two years (13 October 1977 and 12 September 1978), the samples were transported directly to the laboratory, cleaned from ingrown moss and other plants as well as small particles that had penetrated the litter-bag. The weight loss was determined on individual samples after drying to constant weight at 85 °C. All storage for more than one day was at −20 °C.

The chemical analyses were made on composite samples from each treatment. Analyses of nitrogen in litter and lignin were made by the Kjeldahl method. Extractives, lignin and polymer carbohydrates were determined as described by Berg (1978).

3.3. Soil microorganisms

For microbial biomass determinations, soil samples were taken with a steel corer. Five cores were taken from each plot and divided in A_{01}—A_{02}, A_2 and B horizons. Composite samples were made from corresponding soil layers in each plot. The fungal biomass was estimated in all three horizons, while bacterial biomass determinations were made only in the A_{01}—A_{02} horizon.

Total fungal lengths (living and dead mycelium) were determined with the agar-film technique (Jones & Mollison 1948). The preparation method and counting procedure were described by Bååth & Söderström (1979). Acitve fungal mycelium was estimated with the fluorescein diacetate (FDA) staining method (Söderström 1977) after sample preparation according to Söderström (1979). The mean hyphal diameter in the A_{01}—A_{02} horizon was 2.0 μm in all treatments and assumed to be the same in the other soil layers. A density of 1.1 g cm^{-3} and a dry weight of 15% of wet weight was used for biomass calculations (Bååth & Söderström 1979).

Number and biomass of bacteria were measured by the direct counting method described by Trolldenier (1972) as modified by Clarholm & Rosswall (1980). The stained smears were studied in an epifluorescence microscope. In each sample the cells were separated into five size classes, and from these the mean cell size per treatment was calculated. A density of 1.3 g cm^{-3} and a dry weight of 20% of wet weight was used for biomass calculations (Faegri et al. 1977).

Physiological characteristics of the bacterial populations were determined on bacterial strains isolated from soil samples from the $A_{01}-A_{02}$ horizon; three samples from the Control plots and three from the Acid 3 plots.

One hundred bacterial isolates from each sample were isolated according to Clarholm & Rosswall (1973). Fifty-four physiological tests on the isolates were made with a multipoint test procedure using microtitre plates with 96 wells (cf. Table 6). The results of 33 tests were treated by a factor analytical method (Rosswall & Kvillner 1978) using a standard programme with certain additional sub-routines (Persson & Rosswall 1978). Some strains died before all tests could be performed, and only 451 strains were included in the final data analysis.

3.4. Soil fauna

Enchytraeid samples were taken, seven per plot, using a soil corer with an area of 22.0 cm². The cores were taken as deeply as possible in this stony moraine i. e. 10−15 cm. They were divided into three soil layers, $A_{00}-A_{02}$, A_2 and B, which were put into separate plastic vials for transportation.

The enchytraeids were extracted from the soil with a modified Baermann technique (O'CONNOR 1962), counted and classified to species according to NIELSEN & CHRISTENSEN (1959).

Sampling for microarthropods was made with a soil corer (surface area 10.8 cm²) to a depth of 10 to 12 cm. The cores were divided into 2 cm thick slices in the laboratory and animals were extracted with a modified 'Macfadyen high gradient canister extractor' (PERSSON & LOHM 1977).

4. Results

4.1. Litter decomposition

After two years incubation, there was a significantly lower decomposition in the Acid 1 and Acid 3 plots compared to Controls (Table 4). A tendency for similar results was noticed already after one year for both kinds of litter used. Liming resulted in decreased decomposition, although it was not significant.

The chemical analyses did not reveal any definite difference in composition between the litters from the control and acidified plots (Table 4). Of the organic fractions analysed — water and acetone solubles, Klason lignin, and the different polymer carbohydrates — there was a strong increase in the analytical Klason lignin fraction in the root litter, but no noticeable difference between treatments.

The analyses for total nitrogen in the needle litter decomposed for two years might indicate a lower nitrogen retention in the needle litter on the acidified plots.

4.2. Soil microorganisms

FDA-active mycelium decreased with increasing soil acidification, and this applied to all three soil layers (Table 5). Significant differences (based on log transformed data) compared to the Control were found in the A_{01}—A_{02} and the A_2 horizons.

Table 4. One-year and two-year weight losses and remaining amounts of Klason lignin extractives and nitrogen in needle and root litter

	One year						Two years				
	Initial material	A Control	B Lime	C Acid 1	D Acid 3	s. e.	A Control	B Lime	C Acid 1	D Acid 3	s. e.
Needle litter:											
Weight loss (%)	*0.0*	*20.3*	*20.1*	*19.2*	*18.9*	*0.6*	*39.5*^{CD}	*36.1*	*34.9*^{A}	*32.2*^{A}	*1.3*
Water and acetone soluble material (%)1)	*15*	*16*	*15*	*14*	*15*		*12*	*12*	*12*	*12*	
Klason lignin (%)1)	*26*	*34*	*33*	*32*	*33*		*36*	*37*	*37*	*36*	
Klason lignin (mg)2)	260	270	260	260	270		230	240	240	250	
Total nitrogen (%)1c	*0.42*	*0.54*	*0.56*	*0.52*	*0.54*		*0.73*	*0.70*	*0.66*	*0.62*	
Total nitrogen (mg)2)	4.2	4.3	4.5	4.2	4.4		4.7	4.5	4.3	4.3	
Lignin nitrogen (%)3)	*0.58*	*0.56*		*0.59*	*0.56*		*0.65*	*0.68*	*0.65*	*0.64*	
Lignin nitrogen (mg)2)	1.6	1.5		1.5	1.5		1.5	1.6	1.6	1.6	
Root litter:											
Weight loss (%)	*0.0*	*30.9*			*24.5*	*2.5*					
Water and acetone soluble material (%)1)	*29*	*7*			*7*						
Klason lignin (%)1)	*21*	*39*			*37*						
Klason lignin (mg)2)	210	280			290						
Total nitrogen (%)1)	*0.31*	*0.47*			*0.42*						
Total nitrogen (mg)2)	3.1	3.3			3.2						
Lignin nitrogen (%)3)	*0.52*	*0.43*			*0.44*						
Lignin nitrogen (mg)2)	1.1	1.2			1.3						

Note. — Statistical treatment, see legend to Table 3.

1) Percent of litter remaining; 2) Calculated to be in the remains from 1 g initial litter; 3) Percent of the lignin fraction.

Table 5. Mycelial lengths and bacterial numbers and their amounts of biomasses in different soil layers at Norrliden expressed per g dry weight of soil

		A	B	C	D	
		Control	Lime	Acid 1	Acid 3	s. e.
FDA-active fungal mycelium (m)	$A_{01}-A_{02}$	250^{D}	210	220	150^{A}	33
	A_2	25^{CD}	27^{CD}	14^{AB}	13^{AB}	3.8
	B	6.1	4.0	4.5	3.1	1.5
Total fungal mycelium (m)	$A_{01}-A_{02}$	3700	3700	4300	4600	550
	A_2	820^{D}	570	710	500^{A}	93
	B	140^{BCD}	340^{AD}	360^{AD}	570^{ABC}	45
FDA-active of total (%)	$A_{01}-A_{02}$	*6.7*	*5.9*	*5.2*	*3.3*	
	A_2	*3.2*	*4.7*	*2.2*	*2.6*	
	B	*4.8*	*1.2*	*1.3*	*0.5*	
FDA-active fungal biomass (μg dw)	$A_{01}-A_{02}$	130	110	110	78	
	A_2	13	14	7.3	6.6	
	B	3.2	2.1	2.3	1.6	
Total fungal biomass (μg dw)	$A_{01}-A_{02}$	1900	1900	2200	2400	
	A_2	420	300	370	260	
	B	74	170	190	300	
Bacteria (number $\times 10^{-9}$)	$A_{01}-A_{02}$	12.6^{D}	12.4^{D}	n. d.	6.6^{AB}	1.0
Bacterial biomass (μg dw)	$A_{01}-A_{02}$	700^{D}	560^{D}	n. d.	180^{AB}	48

Note. — Statistical Treatment, see legend to Table 3.

Total mycelium (live and dead) increased with increasing soil acidification in the A_{01}—A_{02} and the B horizons, with a significant difference in the B layer. In the A_2 horizon less total mycelium was found in Acid 3 compared to the Control. In all horizons the percentages of FDA-active hyphae of total hyphae were lower in the acidified plots compared to the Control.

Bacterial numbers and biomasses were only determined in the A_{01}—A_{02} horizon. In Acid 3 treatment the bacterial numbers were reduced to almost half the number in the Control (Table 5). The differences in bacterial biomass were even more pronounced, since the bacteria in Acid 3 treatment were considerably smaller than in the Control. The mean bacterial dry weight in the Control was estimated to be 56×10^{-15} g per bacterial cell compared to 27×10^{-15} g in Acid 3 treatment.

Neither the bacterial nor the fungal biomass appeared to be influenced to any great extent by liming. Only the total fungal mycelium in the B horizon was significantly higher than in the Control (Table 5).

The acid treatment caused marked changes in the physiological abilities of the soil bacterial populations (Table 6). Eight of the 54 tests showed a significantly greater percentage of positive results in populations from the Control compared with the Acid 3 treatment, while 10 tests showed a significantly higher proportion of positive test results from isolates from Acid 3 treatment. Gram negative bacteria were more numerous in the Control plots (tests 49, 50, 51 & 52), while spore-forming bacteria appeared to prevail in the acid treated plots (test 53).

The isolated bacteria were unable to grow at low *p*H values (*p*H 3.5 and 4.0). Other tests giving a low number of positive results were: growth at 48 °C; hydrolysis of cellulose and aesculin; growth on acetate, benzoate, oxalate, vanillic acid and vanillin as sole carbon sources; growth on "nitrogen free" medium and denitrification.

In the factor analysis only 33 tests were included (tests underlined in Table 6); the others were omitted due to zero positive results in any one of the six populations. The factor analysis of the test results of 451 strains on 33 tests is based on a correlation matrix between the tests. The matrix was condensed into ten principal axes (factors) and the position of each individual bacterial isolate in the hyperellipse made up of the ten factors was calculated. The mean values for the six populations in relation to the first five factors showed significant differences between the Control and Acid 3 populations along factors 1, 3 and 5.

Table 6. Per cent positive results of 54 physiological tests on 451 isolates from Control. and Acid 3 plots[1]

Test		Control	Acid 3
	Number of isolates:	219	232
1.	Growth at *p*H 3.5	0	0
2.	Growth at *p*H 4.0	0	0
3.	Growth at *p*H 4.5	5	2
4.	Growth at *p*H 5.0	21	3[2]
5.	Growth at *p*H 5.5	59	25
6.	Growth at *p*H 6.0	68	66
7.	Growth at *p*H 9.0	36	65
8.	Growth at 2 °C	65	81[2]
9.	Growth at 5 °C	70	85[2]
10.	Growth at 37 °C	3	12[2]
11.	Growth at 48 °C	0	1
12.	Hydrolysis of cellulose	0	0
13.	Hydrolysis of chitin	13	31[2]
14.	Hydrolysis of starch	27	59[2]
15.	Hydrolysis of casein	6	8
16.	Hydrolysis of gelatin	9	21[2]
17.	Hydrolysis of aesculin	1	2
18.	Acid production from glucose, aerobically	64	52[2]
19.	Acid production from glucose, anaerobically	4	6
20.	Acid production from arabinose	18	25
21.	Acid production from cellobiose	70	56
22.	Acid production from galactose	55	48
23.	Acid production from maltose	72	54
24.	Acid production from mannose	50	37[2]
25.	Acid production from melizitose	9	23[2]
26.	Acid production from rhamnose	13	15
27.	Acid production from sucrose	10	39[2]
28.	Acid production from xylose	48	43
29.	Acetate as sole carbon source	2	2
30.	Benzoate as sole carbon source	0	0
31.	Citrate as sole carbon source	11	9
32.	Gluconate as sole carbon source	21	39[2]
33.	Lactate as sole carbon source	9	10
34.	Oxalate as sole carbon source	1	1
35.	p-Hydroxy benzoic acid as sole cabron source	9	9
36.	Protocathecnic acid as carbon source	5	8
37.	Vanillic acid as carbon source	1	0
38.	Vanillin as sole carbon source	1	1
39.	Growth on "nitrogen free" medium	1	0
40.	Ammonification	57	28
41.	Denitrification	1	0
42.	H_2S production from cystein	1	6
43.	Presence of acetamidase	5	5
44.	Presence of catalase	49	30[2]
45.	Presence of cytochrome oxidase	10	0[2]
46.	Presence of oxidase	8	0
47.	Presence of phosphatase	66	52
48.	Growth on King's agar	3	1
49.	Growth on medium for fluorescent *Pseudomonas* spp.	6	3[2]
50.	Growth on medium for *Pseudomonas* spp.	7	0[2]
51.	Resistence to thionine	12	3[2]
52.	Resistence to penicillin	50	23
53.	Presence of spores	10	49[2]
54.	Reduction of methylene blue	8	7

1) Results from the 33 tests, indicated by bold numbers, were used in the factor analysis.

2) Significant difference at the level $p < 0.05$.

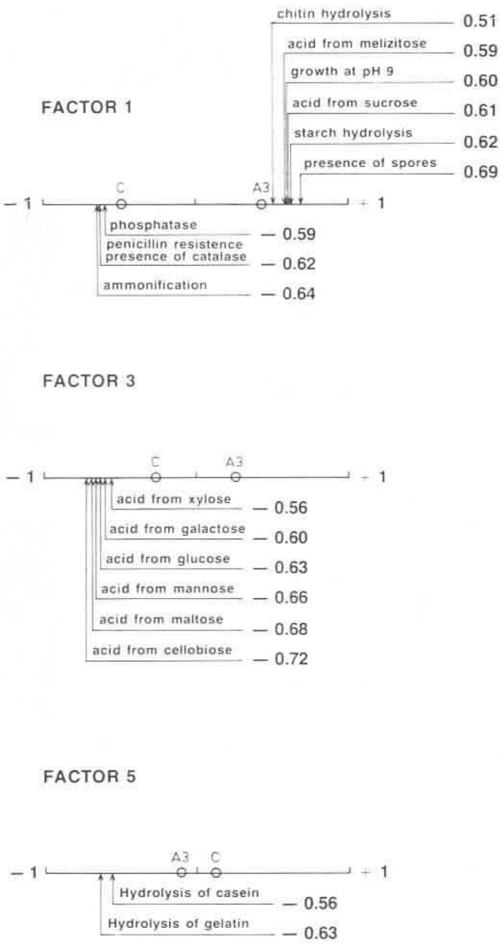

Fig. 1. Graphical presentation of the heaviest factor loadings on the three factors showing significant differences between bacterial populations from Control and Acid 3 plots. Mean values for factor scores of the Control bacteria (C) and bacteria from Acid 3 (A3) plots are also indicated.

The factors can be characterized by looking at the so-called factor loadings of the individual test (Fig. 1). Factor 1 was thus characterized by spore formers and hydrolytic ability. Factor 3 was characterized by low ability to form acid from sugars and factor 5 of a low proteolytic activity. The mean position of the Control populations (C) and Acid 3 populations (A3) along the three factors with significant differences between the two sets of populations are given in Fig. 1.

The bacteria from the Acid 3 plots were characterized by presence of spore formers, and by their abilities to hydrolyse starch, chitin and proteins, but had a low ability to form acids from simple sugars. The bacteria from the Control plots characteristically possessed the enzymes phosphatase and catalase and were also able to form ammonia from simple nitrogenous organic compounds.

4.3. Soil fauna

The enchytraeid populations in all treatments were dominated by *Cognettia sphagnetorum* (Vejd.). A few specimens of *Bryodrilus ehlersi* Ude and *Mesenchytraeus* spp. were also found in all treatments. The abundance of enchytraeids in different soil horizons and treatments is given in Table 7.

Table 7. Abundance of Enchytraeidae in different soil layers at Norrliden (number m^{-2})

	A Control	B Lime	C Acid 1	D Acid 3	s. e.
Cognettia sphagnetorum					
$A_{00}-A_{02}$	11200^{BCD}	860^{AC}	6260^{ABD}	1260^{AC}	1070
A_2	6000^{BD}	1020^{AC}	6720^{BD}	670^{AC}	1300
B	280	20	280	20	100
Total number	**17490^{BD}**	**1910^{AC}**	**13260^{BD}**	**1950^{AC}**	**2020**
Other species					
$A_{00}-A_{02}$	50	110	50	50	50
A_2	0	0	0	60	30
B	0	0	0	0	0
Total number	**50**	**110**	**50**	**110**	**60**
Enchytraeidae, total					
$A_{00}-A_{02}$	11240^{BCD}	970^{AC}	6310^{ABD}	1300^{AC}	1070
A_2	6000^{BD}	1020^{AC}	6720^{BD}	740^{AC}	1310
B	280	20	280	20	100
Total number	**17530^{BD}**	**2020^{AC}**	**13300^{BD}**	**2060^{AC}**	**2020**

Note. — Statistical treatment, see legend to Table 3. In tables 7—9 differences between total abundances and sums of species/group abundances are due to rounding errors when numbers per soil core are converted to numbers per m^{-2}.

The total population of enchytraeids and the population of *C. sphagnetorum* showed the same differences in abundance between treatments. The abundance of other enchytraeid species than *C. sphagnetorum* was not significantly different between treatments. The vertical distribution of *C. sphagnetorum* was remarkable in the Lime and Acid 1 treatments where the main part of the population was found in the A_2 horizon. Normally *C. sphagnetorum*, as most enchytraeid species, is most abundant in the litter- and humus layers (e.g. ABRAHAMSEN 1972). This was also the case in the Control and Acid 3 treatment. In the A_{00}—A_{02} horizon the enchytraeid population was significantly lower in all treatments compared to the Control. However, in the other two soil horizons, as well as in the total soil profile, the Control and Acid 1 treatments did not differ in abundance whereas the Lime and Acid 3 treatments were both lower in abundance of enchytraeids.

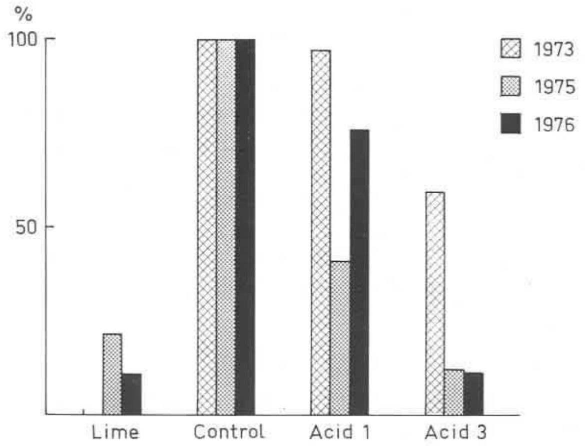

Fig. 2. Occurrence of *C. sphagnetorum* in different treatments at three autumn samplings given as percentages of the abundance in the corresponding Control plots.

Table 8. Abundance of Collembola at Norrliden (number m^{-2})

	A Control	C Acid 1	D Acid 3	s. e.
Hypogastrura inermis Tullb.	60	0	0	30
Xenylla börneri Axels.	2290	440	0	1170
Willemia aspinata Stach	0	120	0	70
W. anophthalma Börner	5810	1050	1050	2130
Friesea mirabilis Tullb.	0	680	60	390
Anurida pygmaea Börner	1420	5620	1170	1130
Onychiurus absoloni Börner	620	1110	440	240
O. armatus-group	0	250	0	90
Tullbergia krausbaueri Börner	6920^{D}	21420	36300^{A}	4170
Anurophorus septentrionalis Palissa	5740	4070	4140	1590
A. binoculatus Kseneman	3330	2590	890	1140
Folsomia litsteri-group1)	3080	2470	1420	1090
Isotomiella minor Schäffer	2660	1620	1550	560
Isotoma notabilis Schäffer	440	370	60	170
I. viridis Bourl.	120	190	190	60
Orchesella bifasciata Nicolet	120	0	0	70
Lepidocyrtus lignorum Fabr.	440	250	310	130
L. cyaneus Tullb.	0	0	60	30
Megalothorax minimus Willem.	60	60	60	60
Collembola, total	**33270**	**42710**	**48270**	**5120**

Note. — Statistical treatment, see legend to Table 3.

1) *F. litsteri*, Bagnall plus at least one more species (resembling *F. bisetosa* Gisin).

The 1976 abundance data for the different treatments are compared with the corresponding data from October 1973 and 1975 (Lundkvist 1977) in Fig. 2. As between-year variation in the enchytraeid population could be considerable, the abundances are given as percentages of the Control plots for the three years.

There were no differences as regard total numbers of springtails and mites between treatments (Tables 8 and 9). The dominant springtail, *Tullbergia krausbaueri*, showed a significant increase in the acidified plots. Among the mites adults of *Oppia obsoleta* and a mesostigmatid species of the genus *Trachytes* decreased.

When the abundances in each soil horizon were tested separately, significant differences between treatments were found in the A_2 horizon for *Tullbergia krausbaueri*, *Anurida pygmaea*. *Nanorchestes arboriger*, *Tectocepheus velatus* and the group Oppioidea. If the differences in thickness of the A_2 horizons were taken into consideration, numbers of Oppioidea were not significantly different. *T. krausbaueri* and *T. velatus* had higher abundances in the A_2-horizon of the acidified treatments and this pattern can also be seen in the other horizons, though the differences in total abundances are significant only for *T. krausbaueri*. *A. pygmaea* had about the same abundance in Acid 3 plots and Control plots and a higher abundance in Acid 1 plots. This pattern could be seen in all horizons but was statistically significant only in the A_2 horizon. *N. arboriger* showed the same pattern as *A. pygmaea* in the A_2 horizon. In the other horizon *N. arboriger* had a lower abundance in Acid 3 plots than in Control and Acid 1 plots.

4.4. Soil characteristics

After six years of treatment with acid the A_{00} horizon was 0.5—1.0 cm thinner in Acid 3 plots than in Control plots (Table 3). For the humus layer (A_{01}—A_{02}) there was a similar tendency, while the bleached layer (A_2) was significantly thicker in the acid treatments. Liming decreased the thickness of the organic horizons, while the elluvial horizon was unchanged. Admittedly the method of measuring soil profile changes has several objections and the absolute rate of change could be questioned.

Table 9. Abundance of Acari at Norrliden (number m^{-2}).

	A	C	D	
	Control	Acid 1	Acid 3	s. e.
MESOSTIGMATA				
Zerconidae spp. (mostly *Parazercon sarekensis* Willm.)	3400	2590	1300	670
Other Gamsina	1050	1170	1550	430
Trachytes sp.	1110^{CD}	120^{A}	60^{A}	190
Other Uropodina	490	120	60	280
Mesostigmata, **total**	**6180**	**4010**	**2900**	**940**
ASTIGMATA				
Schwiebea sp.	23270	20810	17900	4190
Rhizoglyphus sp.	120	0	0	70
Astigmata, **total**	**23390**	**20810**	**17900**	**4240**
PROSTIGMATA				
Nanorchestes arboriger Berl.	26730	24320	10000	5020
Scutacaridae sp.	120	860	120	200
Prostigmata, **total**1)	**117340**	**106670**	**52780**	**17900**
CRYPTOSTIGMATA				
Paleacarus histricinus Träg., ad. + juv.	370	190	190	160
Phthiracarus spp. ad.	250	190	190	80
Mesotritia testacea Forssl., ad.	0	190	0	160
Euptyctima, juv.	440	990	60	440
Brachychthoniidae spp., ad. + juv.	50370	28950	31480	9640
Trhypochthonius cladonicola Willm., ad. + juv.	680	490	930	420
Camisia biurus Koch, ad.	310	0	0	170
Heminothrus paolianus Berl., ad.	60	120	0	60
Nothroidea spp. juv.	310	210	310	160
Nanhermannia sellnicki Forssl., ad.	490	620	1110	230
N. sellnicki, juv.	1230	1300	4820	1510
Belbidae sp., ad. + juv.	370	120	0	70
Porobelba spinosa Selln., ad.	60	60	0	30
Eremeus silvestris Forssl., ad.	0	250	60	80
Carabodes spp., ad.	11360	10680	2660	4010
Tectocepheus velatus Mich., ad.	9630	13210	14140	2710
T. velatus, juv.	46420	78400	61670	10230
Oppia nova Oudem., ad.	13450	14440	19070	3810
O. obsoleta Paoli, ad.	740^{CD}	0^{A}	120^{A}	110
Suctobelba spp., ad.	7220	5860	1970	1200
Autogneta parva Forssl., ad.	930	620	2340	850
A. trägårdhi Forssl., ad.	440	190	440	190
Oppioidea spp., juv.	10120	9940	14630	4710
Adoristes ovatus Koch, ad.	190	190	60	120
Hemileius initialis Berl., ad.	1670	560	370	370
Scheloribates laevigatus Koch, ad.	60	0	310	60
Chamobates inscisus van der Hammen, ad.	1790	1790	2160	590
Ceratozetes thienemanni Willm., ad.	680	120	310	170
Trichoribates trimaculatus Koch, ad.	60	0	60	60
Eupelops acromios Hermann, ad.	0	190	60	70
Galumnidae sp., ad.	0	60	60	60
Other Cryptostigmata, juv.	8210	7290	5120	1270
Cryptostigmata, **total**	**168020**	**177290**	**164880**	**10620**
Acari, **total**	**314940**	**308770**	**238450**	**20870**

Note. — Statistical treatment, see legend to Table 3.

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1) Prostigmata total includes undetermimed individuals.

5. Discussion

5.1. Decomposition rates and chemical changes

The experimental acidification took place before the decomposition experiments were started. This means that no acid was distributed on the needle litter samples. Furthermore, since the needle litter-bags were placed on the newly fallen autumn litter, there were no direct contacts between the litter-bags and the soil material subjected to acidification. It is therefore noticeable that decreased decomposition rates in fact were observed in the acid treated plots. One explanation of these results could be the almost complete absence of a field layer, but effects due to a changed soil situation cannot be excluded.

For the root litter, a changed weight loss rate due to acidification appeared much more reasonable, since more drastic effects could be expected in the A_{01}—A_{02} layer which had been affected by six consecutive years of acid treatment. This reduced weight loss was probably due to decreased microbial activities, indicated by the lower microbial biomasses in the acid treatments (Table 5). A consequence of the lower decomposition rate would be a longer retention time for the organic material in litter form, thus a slower turn-over.

There was a somewhat higher retention of nitrogen in the needle litter of the limed plots compared to those that were heavily acidified (Table 4). This observation must be regarded only as a pointer and to confirm any such tendency longterm decomposition studies would be necessary.

5.2. Soil microorganisms

The artificial acidification lowered the amount of FDA-active fungi and the number of bacteria, indicating a decreased microbial activity and productivity. A decreased fungal productivity is generally believed to result in lower amounts of total fungal hyphae. This did not, however, seem to be the case in the acidified plots. On the contrary, somewhat higher amounts were registered in the A_{01}—A_{02} and the B horizons; in other words, inactive and dead fungal hyphae had accumulated in these layers. This might also be due to a lower decomposition rate of fungal mycelium, as suggested by Bååth & Söderström (1979).

The accumulation of dead fungal hyphae and the decrease in FDA-active mycelium and bacterial numbers in the acidified plots indicated that the decomposition of organic material by microbial action was lower in these plots compared to the Control. This assumption was confirmed by the lower rates of weight loss of pine needles and root litter in the acid treated plots (Table 4).

It is interesting to note that the liming of the soil did not result in any large effects on the microbial biomass, in spite of the rather drastic increase in soil *p*H (Tables 3 and 5). A further confirmation that no major change in microbial activity had occurred was also provided by the data for weight loss of pine needles in the Lime and the Control plots (Table 4).

The differences in fungal biomasses in the A_{01}—A_{02} horizon between the treatments were effects of varying hyphae lengths, as the hyphal diameter did not differ between the plots. In contrast to the fungi, the decrease in bacterial biomass due to the acidification was an decrease in bacterial biomass due to the acidification was an effect of both a lowered bacterial number and a smaller cell size. Several explanations could be found for the decreased bacterial cell sizes. Casida (1977) and MacKelvie et al. (1968) showed that bacteria grown in more meagre substrates became smaller. Thus the artificial acidification might have caused less suitable conditions, resulting in smaller cells. However, the difference in cell size could also be an effect of altered bacterial populations, as indicated by the factor analysis.

Significant differences between the bacterial populations from the Control and Acid 3 plots were detected in the physiological characteristics of the bacteria isolated from the plots. There was no indication of an adaptation to the acid environment based on the ability of the bacteria to grow on acidified culture media. It is possible that the acid treatment killed a large proportion of vegetative bacterial cells, but spores could have survived and could later germinate and proliferate at the expense of the gram-negative bacteria. The resulting shift in the population might have affected the nitrogen transformations of the soil, as there was a decrease in ammonifiers after acid treatment.

The observed decreases in plant litter decomposition rates could not be directly supported by observed changes in bacterial populations, as a larger proportion of the bacteria isolated from Acid 3 plots showed hydrolytic abilities. It should be remembered, however, that only a small portion, perhaps 1 %, of the soil bacteria was investigated by the techniques used and that the study showed changes in physiological abilities only — not in activity. The observed decrease in total numbers of bacteria after acid treatment by 50 % (Table 5) could thus have occurred selectively without it being observed by the physiological characterization of isolates.

5.3. Soil fauna

The observed populations decrease of *C. sphagnetorum* was well in accordance with earlier results from experimental acidification, e. g. Lundkvist (1977) at the present site and Hågvar & Abrahamsen (1977). At another pine stand in Central Sweden (Lundkvist, unpublished data but cf. Lohm et al. (1977) for site description) the abundance of *C. sphagnetorum* was reduced by 90 % after three yearly treatments of sulphuric acid with 100 kg, 50 kg and 100 kg · ha^{-1} respectively.

In the early phase after acid treatment the *p*H-induced changes in the soil that affected the enchytraeid population might be of physical-chemical character.

As the enchytraeids are softbodied animals living in contact with the water phase of the soil they are sensitive to changes in the soil water conditions, e. g. a decrease in *p*H. Hågvar & Abrahamsen (1977) have shown that an isotonic water solution of *p*H 2 causes death of *C. sphagnetorum* within a day, while it survives 3—4 days at *p*H 3.

Increased soil water acidity will also cause increased ion exchange in the soil which in turn causes higher osmotic potential in the soil water. This "salt effect" is regarded as possibly detrimental to the enchytraeids by other kinds of environmental influences, e. g. fertilization (Lohm et al. 1977). Abrahamsen (1971) has shown that *C. sphagnetorum* does not survive greater soil water retaining forces than 10 bar (pF ca. 4). The decrease in abundance of *C. sphagnetorum* could hence be interpreted as the remains of a shock effect due to very high H^+-ion concentrations following immediately upon treatments with sulphuric acid once or three times a year.

However, *C. sphagnetorum* appears to have a good capacity to recover as the species reproduces through fragmentation and its population normally fluctuates a great deal even between months (Standen 1973).

Thus, more long-lasting *p*H-effects on the total soil system are more plausible explanations of the population decrease. These long scale changes affecting the enchytraeids might be of physical-chemical and/or biological character.

The hypothesis of a "salt effect" on the enchytraeids is valid also for the decrease in abundance at the Lime treatment. It might also explain the differing vertical distribution of enchytraeids in this treatment. The added limestone was of a coarse structure and solid limestone still remained on the ground five years after application and thus could cause raised osmotic potential at soil microsites for a long time especially in the upper soil horizon.

C. sphagnetorum is generally believed to feed on litter and/or micro-organisms (Springett & Latter 1977; Standen & Latter 1977; Latter & Howson 1978). The decrease in abundance of *C. sphagnetorum* at the acidified and limed plots could thus also be explained by the observed decrease in the microorganism populations. No correlation was, however, found between the abundance of *C. sphagnetorum* and any of the fungal or bacterial amounts or biomasses. But as *C. sphagnetorum* has been shown to prefer litter in later stages of decomposition (Standen & Latter 1977; Latter & Howson 1978) the decreased rate of decomposition in Acid 1 and Acid 3 treatments as well as the decrease in organic soil layers in Acid 3 and Lime treatments might have reduced food availability for *C. sphagnetorum*.

The reason for the changed vertical distribution of *C. sphagnetorum* in the Acid 1 treatment is not obvious. Possibly the acid treatment had affected the A_{00}—A_{02} horizon more than the A_2 horizon so that the enchytraeid population had suffered, for some of the reasons discussed above, in the former but not in the latter soil layer. This gradual effect would be masked in the overall damage caused to the enchytraeid population in the Acid 3 treatment.

In coniferous forests, HÅGVAR & ABRAHAMSEN (1977) found no differences in total abundance of mites in acidified plots, while springtails increased with acidification in two of three experiments. Our results are in good agreement with theirs. Even if the increase in total Collembola in our study was not significant, significant changes due to the acidification were found on the species level. *T. krausbaueri*, often the most abundant springtail species in coniferous forest soil, had higher abundance in the acidified plots. This species has a thin cuticle and could therefore be more susceptible to chemicals. However, it lives in a wide range of depths in the soil and is perhaps better protected from disturbances than a typical surface-dweller.

Reduced predation or competition from other species may increase the abundance of a species. In this study no drastic changes in abundances of possible competitors or predatory mesostigmatid mites were found. Predatory prostigmatid mites were not counted separately, partly because feeding habits of many Prostigmata are unknown. The families Bdellidae and Cunaxidae are known to be predators on microarthropods, but only a few Bdellidae were found in Acid 1 plots. However, other predatory arthropods such as spiders were not investigated. Reduced predation cannot therefore be ruled out as an explanation of the increased abundance of *T. krausbaueri*. Populations of other species with similar size and lifeforms, such as *W. anophthalma*, *A. binoculatus* and *O. absoloni*, were not increased.

Most non-predatory microarthropods are probably fungivores. Results of correlation tests between arthropods species or groups and hyphal lengths are given in Table 10.

T. krausbaueri showed positive correlation with total mycelium in the A_{00}—A_{02} horizon, suggesting that this species can feed on dead mycelium. This could explain the higher abundances in acidified plots.

The negative correlation between some microarthropods and FDA-active fungal mycelium in the A_2 horizon as well as the differences between correlation coefficients of the A_2 horizon and the other horizons for other species are difficult to explain. It could, for instance, indicate that some fungal species in A_2 were toxic or at least less suitable as food for microarthropods.

The positive correlation between some microarthropods and active mycelium might indicate that the reduction of microarthropod populations was due to a reduction of the active part of fungal mycelium. There is no evidence that most animals feed primarily on the active mycelium but it is reasonable to assume that this is the case. Correlation between variables can of course be the result of independent reactions to a common external factor e.g. direct and indirect chemical effects on both microarthropods and fungal mycelium (cf. the discussion about enchytraeids). Movements of the animals between soil layers also complicate the interpretation of these results.

5.4. Concluding remarks

The treatment with sulphuric acid, particularly Acid 3, influenced different soil biological properties significantly. The decomposition rate was lowered, the microorganism populations were reduced and the composition of the soil fauna populations changed. Hence, a total decrease of activity was observed as a result of the treatment. If a lowered activity remains prelavent, then a decreased site fertility will be a consequence (cf. TAMM 1976).

From our results it was not possible to conclude that the changes in siol biological properties were entirely due to the increasing supply of H^+ ions. The acid was distributed as H_2SO_4 and it cannot be excluded that the added sulphate could have had negative effects on soil organisms. Qualitative and quantitative changes in the input of plant litter could also be major factors.

The ground and field vegetation were almost totally killed in the Acid 3 treatment. Field observations in 1978, after two years without treatment, indicated however that the ground

Table 10. Correlation coefficients between microarthropod abundances and hyphal lengths in different soil horizons

		Jones-Mollison mycelium	FDA active mycelium
Willemia anophthalama	$A_{00}-A_{02}$	−0.41	0.12
Anurida pygmaea	$A_{00}-A_{02}$	0.08	0.17
Anurida pygmaea	A_2	−0.10	−0.21
Tullbergia krausbaueri	$A_{00}-A_{02}$	0.76[1]	−0.17
Tullbergia krausbaueri	A_2	−0.28	−0.76[1]
Tullbergia krausbaueri	B	0.18	−0.40
Anurophorus septentrionalis	$A_{00}-A_{02}$	0.13	0.79[1]
Anurophorus binoculatur	$A_{00}-A_{02}$	−0.25	0.35
Anurophorus binoculatur	A_2	0.46	0.35
Folsomia litsteri-group	$A_{00}-A_{02}$	−0.31	0.76[1]
Isotomiella minor	$A_{00}-A_{02}$	−0.08	0.48
Collembola, total	$A_{00}-A_{02}$	**0.59**	**0.31**
Collembola, total	A_2	**−0.05**	**−0.50**
Collembola. total	B	**0.11**	**−0.41**
Nanorchestes arboriger	$A_{00}-A_{02}$	−0.37	0.83[1]
Nanorchestes arboriger	A_2	0.16	−0.43
Nanorchestes arboriger	B	−0.49	0.62
Prostigmata, total	$A_{00}-A_{02}$	**−0.27**	**0.96**[1]
Prostigmata, total	A_2	**0.35**	**−0.29**
Prostigmata, total	B	**−0.61**	**0.66**
Astigmata, total		**—0.06**	**0.69**[1]
Astigmata, total	A_2	**−0.17**	**0.07**
Astigmata, total	B	**−0.29**	**0.68**[1]
Branchychthoniidae spp.	$A_{00}-A_{02}$	−0.10	0.72[1]
Branchychthoniidae spp.	A_2	−0.44	−0.43
Branchychthoniidae spp.	B	−0.53	0.70[1]
Carabodes spp.	$A_{00}-A_{02}$	−0.05	0.73[1]
Tectocepheus velatus	$A_{00}-A_{02}$	0.32	0.23
Tectocepheus velatus	A_2	−0.33	−0.48
Oppioidea spp.	$A_{00}-A_{02}$	0.36	0.39
Oppioidea spp.	A_2	−0.05	−0.45
Oppioidea spp.	B	−0.51	0.64
Cryptostigmata, total	$A_{00}-A_{02}$	**0.28**	**0.64**
Cryptostigmata, total	A_2	**−0.29**	**−0.61**
Cryptostigmata, total		**—0.51**	**0.73**[1]
Acari, total	$A_{00}-A_{02}$	**- 0.07**	**0.84**[1]
Acari, total	A_2	**−0.02**	**−0.46**
Acari, total	B	**−0.57**	**0.75**[1]

1) Significance at the level $p < 0.05$ (d. f. 7).

vegetation had started to recover. Further studies have been initiated to verify the indicated increase of the elluvial horizon.

The relevance of our results in relation to the occurring acid deposition could be a matter for discussion. It appears, however, that one cannot preclude the possibility that acidification may have a marked influence on the processes in the below-ground ecosystem and consequently, in a longer time perspective, on the whole terrestrial ecosystem.

6. Summary

The effects of artificial acidification and liming on soil organisms and decomposition rates were determined in a field experiment in a pine forest podzol Acidification lowered the decomposition rate of both needle and root litter, whereas liming had less effect. FDA-active fungal lengths as well as bacterial numbers and cell size decreased in the acidified plots compared to the Control. Liming had no marked effect on the microorganisms. There were significant changes in the functional characteristics of the bacterial population due to the acid treatment as determined by factor analyses. The abundance of Enchytraeidae decreased drastically both in the acidified and the limed plots. The acidification caused an increase in numbers of Collembola, which was entirely due to an increase in abundance of *Tullbergia krausbaueri*. The number of mites was unchanged but *Trachytes* sp. and *Oppia obsoleta* ad. decreased in the acidified plots. The *p*H of the soil was only slightly lowered by the acid treatment, while liming increased the *p*H considerably.

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